

Illumination Devices Comprising White Light Emitting Diodes and Diode Arrays and Method and Apparatus For Making Them

Field of the Invention

This invention relates to the illumination devices comprising white light emitting diodes ("white LEDs").

Background of the Invention

White LEDs are important in a wide variety of direct and indirect illumination applications. A white LED typically comprises a blue or ultraviolet LED whose emitted light is passed through a phosphor that converts the emitted light to white light. Such LEDs individually or in arrays can be used for room and space illumination, vehicle headlights, signs, and indicators. The emission spectra and color temperature of white LEDs is closer to sunlight than many forms of conventional lighting.

Unfortunately, it is difficult to efficiently make white LEDs enough to compete with conventional light sources. One source of inefficiency is coating the LED with the optimal thickness of phosphor. There should be sufficient phosphor to convert the emitted light but not so much as to block or absorb the white light output. Further details concerning the structure and operation of white LEDs may be found, for example, in United States Patents Nos. 6,576,930; 6,608,332 and 6,614,179 which are incorporated herein by reference.

One approach to coating is to dispose the LEDs on a substrate, to dispense a thick transparent resin layer over the LEDs, and to apply over the transparent layer, a thin layer of resin containing phosphor particles. Ideally the resins dry to form a lens and an outer uniform phosphor layer around the diode. See, for example, United States Patent No. 5,959,316.

There are, however, two problems with this approach. First, the uniformity of the phosphor coating is dependent on the shape of the transparent layer which, in turn, is difficult to control, especially when the resin is dispensed and dried over a wire bonded array. Second, the presence of the intervening transparent layer separates the LED from the phosphor,

causing an undesirable broadening of the effective optical area.

In an attempt to overcome some of these problems, efforts were made to electrophoretically coat the LED with a uniform coating of phosphor. See United States patent No. 6,576,488. However this approach requires selectively masking some portions of the LED structure with conductive material (where phosphor is to be deposited) and other portions with dielectric material. The multiple masking and coating steps add substantially to the time and cost of fabrication.

Accordingly there remains a need for improved white LEDs and LED arrays and for an improved method of fabricating them.

Summary of the Invention

In accordance with the invention, an illumination device comprises a substrate having a surface and a cavity in the surface. At least one light emitting diode (“LED”) is mounted within the cavity, and a monolayer comprising phosphor particles overlies the LED. The phosphor monolayer is adhered to the LED by a monolayer of transparent adhesive material. An optical thick layer of transparent material overlies the phosphor monolayer to encapsulate the LED and optionally to form a lens.

The white LED or LED array can advantageously be fabricated by providing a substrate including one or more LEDs, applying a thin layer of tacky adhesive over the LEDs and applying a thin layer comprising particles of phosphor over the adhesive. The particles adhere to the tacky adhesive in a substantially uniform layer of self-limiting thickness. They selectively adhere where the tacky material is exposed. Advantageously, the thickness of adhesive and particle size are chosen to provide monolayers of desired thickness. Advantageous apparatus for practicing this method is described.

Brief Description of the Drawings

The advantages, nature and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments now to be described in detail in

connection with the accompanying drawings. In the drawings:

FIG. 1 is a schematic cross sectional view of a typical single LED packaged in accordance with the invention;

FIG. 2 is a schematic cross sectional view of a typical array of LEDs packaged in accordance with the invention;

FIG. 3 is a flow chart showing the steps in fabricating a white LED or LED array in accordance with the invention; and

FIG. 4 is a schematic representation of a coating apparatus to facilitate coating the LEDs with phosphor particles.

It is to be understood that these drawings are for purposes of illustrating the concepts of the invention and are not to scale.

DETAILED DESCRIPTION

Referring to the drawings, FIG. 1 is a schematic cross section of an exemplary white light emitting diode (“white LED”) package assembly 100 for creating white light using a LED 101 and a fluorescent converting phosphor particle layer 102. The LED die 101 is placed on and advantageously wirebonded to the surface of a thermally conductive substrate 103 (preferably ceramic) inside a cavity 104. An optical adhesive monolayer 105 is placed on top of the LED body 101 and phosphor particles 106 forming layer 102 are adhered on top of the body. Also shown is an optional encapsulation dome lens 107 encapsulating the coated LED within the cavity 104. The package assembly 100 is composed of substrate 103, a highly reflective layer 108, usually silver, overlying the substrate and a conductive die attach material 109. LED body 102 is typically a nitride LED emitting blue or UV light, and can be connected using a wirebond 110. LED body 101 can have both P and N terminals on the top surface of the LED, in which case two wirebonds 110 will be attached from the top; or it can have both terminals on the bottom surface, using solder-bumping for attachment.

In fabricating the assembly 100, LED body 101 is advantageously covered with a first

sticky transparent material **105**. The transparent material **105** can be covered with a single layer **102** comprising phosphor particles **106**. Once deposited, the particles **106** can create a closed packed structured layer **102** film on top of sticky optical material **105**. Ceramic cavity **104** can optionally then be sealed with a second transparent material **107** that advantageously forms a dome or lens in order to minimize total internal reflection (“TIR”).

FIG. 2 illustrates a multiple LED array assembly **200** in which several LEDs **201**, are placed inside a ceramic cavity **202** similar to the cavity **104** described above. Advantageously, multiple LEDs **201** can be attached on top of a highly conductive substrate **203**, as by conductive epoxy **204**. A transparent adhesive monolayer **205** is placed on top of the multiple LED bodies **201** and a layer **206** of phosphor particles **207** is adhered overlying and over the sides of the bodies **201**. In fabrication, all LEDs **201** can simultaneously be coated with the first tacky transparent material **205**. The particles **207** of the phosphor layer coating can attach to the tacky layer **205** creating a closed packed dense film layer **206**. Then assembly **200** comprising wirebonded LEDs **201** can then optionally be sealed as by covering with a second transparent material **209** that can optionally create a dome or lens. The lens minimizes TIR.

Substrate **203** can be metal, ceramic, multilayer printed wire board, LTCC, HTCC or other suitable thermal conductor. The substrate advantageously includes a heat sink. It can be electrically insulating or electrically conducting. Substrate **203** advantageously comprises a highly thermally conductive metal such as copper, tungsten or molybdenum and/or a highly thermally conductive ceramic such as aluminum nitride (ALN), silicon carbide (SiC) or aluminum oxide (Al_2O_3). In a preferred embodiment it can be nickel-plated copper molybdenum copper clad. Metal powder mixtures such as molybdenum copper, can be used in order to match the thermal expansion coefficient of the LED dies.

It is advantageous to coat and encapsulate in panel form. A panel will contain multiple cavities **202**, each with one or more LED assemblies. The panel is subsequently diced into individual elements **200**. As an example, a panel can contain up to 24 elements ($15.24cm^2$), an element ($1.25cm^2$) can contain 7 cavities and a cavity can hold up to 12 (300 micron) LEDs.

Reflective surface layer **210** can be a coating of metal, such as silver, in a thick or thin film layer overlying the substrate **203**. LED dies **201** can be attached to the package by conductive epoxy **204**, non-conductive epoxy or solder.

Most of the heat generated by the LED during operation can be carried away from the diode through the substrate. Accordingly, it is desirable for the connection between the LED and the substrate to have high thermal conductivity. Some LEDs are fabricated with both electrodes (anode P and cathode N) on the top surface. In such cases electrical connections can be made from the LED **201** to contacts on the substrate using wire bonds **211**. The wire bonds **211** can be ball-wedge and wedge-wedge bonded gold or aluminum wires. Wires **211** can have different thicknesses. Other fabrications can have one electrode on the top face of the LEDs **201** and the second electrode on the bottom. In this case, the connection between the LED **201** and the substrate **203** serves three purposes, first to mechanically attach the LED die to the substrate, second to provide a thermal path from the die into the substrate **203**, and third as an electrical connection to one of the LED electrodes.

The tacky transparent material **205** advantageously is a resin that has an index of refraction (IR) between the LED semiconductor material (3.0-2.8) and the fluorescent material particles **207** (1.77). The tackiness of the material is due to a b-stage or partially cured resin. Tackiness is needed to adhere particles **207**. The material **205** will also serve as a buffer layer as the photons exit the LED junctions and couple with the frequency converting phosphor **207**. The converting phosphor can be particles of YAG:Ce. This structure will maximize the extraction of photons from LEDs **201** and produce a uniform color light distribution.

The preferred tacky transparent materials include but are not limited to partially cured silicones. The silicones can include micro amino emulsions, elastomers, resins and cationics. Other useful polymeric resins include butyral, cellulosic, silicone polymers, acrylate compounds, high molecular weight polyethers, acrylic polymers, co-polymers, and multi-polymers. The index of refraction of the above-mentioned materials can be tailored for optical matching.

Embodiments **100** and **200** depict frequency converting particles deposited on the sides and on top of the LED body. The particles are advantageously single crystal from 5 to 19 micrometers in size preferably in a D:50 particle size distribution. Examples of such phosphor materials suitable for frequency conversion include but are not limited to garnet fluorescent material activated with cerium which can contain Y, Lu, Sc, La, Gd or Sm and an element from Al, Ga and In. Examples of non-garnet materials include Sr_2SiO_4 doped with Eu. There are also organic semi-conducting phosphors for the near UV (360-410) and blue (>410 nm) useable as wavelength converters. These new organic materials can be pulverized into particles and deposited using the techniques disclosed herein.

The optional transparent encapsulant of assemblies **100**, **200** can serve two purposes. The material can seal or encapsulate the cavity containing the coated LEDs, and it can create a lens that minimizes TIR. The index of refraction of the second material preferably lies between the fluorescent material particles (1.77) and air (1.0). The dome shaping of the lens is due to the thixotropic properties of the material. This material is conveniently applied using a manifold syringe on automated equipment. It can alternatively be injection molded as by a steel mold. Useful materials include butyrls, cellulosic polymers, silicone polymers, acrylate polymers, high molecular weight polyethers, and acrylic polymers, co-polymers, and multi-polymers. These materials can be tailored to have optically matched indices of refraction and appropriate viscosities.

Preferably the illumination device is composed of at least one LED, at least one monolayer of transparent tacky material and at least one monolayer comprising frequency converting inorganic particles. The term "monolayer" as used herein refers to a thin film or coating that is less than 25 microns thick. Other layers that can be added include an amorphous film (no definite crystal structure) that conforms or molds to its surroundings. The surface of the LED crystal can be modified by deposition of a monolayer, which may change the reactivity of the LED surface with respect to particles. A surfactant can be used. Surfactants (or surface active agents) are special organic molecules which are made up of two sections: the hydrophilic part (usually ionic or nonionic) which likes water and the hydrophobic part (usually a hydrocarbon chain) which likes oil. The interfacial layer formed

as a result of this is usually a monolayer and allows the particles to adhere to the LED. These monolayers can play an important role in the adhesion process.

The monolayer of frequency converting particles can be a layer of particles or an organic film layer that includes the particles. The adhesion mechanism that holds the particle layer together can involve many mechanisms of particle-to-particle bonding. Among them are mechanical interlocking, molecular forces, Vanderwaals adhesion forces, capillary, electrostatic, magnetic, and free chemical forces. In most cases, the strength of the particle-to-particle bond depends on the contact pressure and surface area of contact between particles. The key is to create a dust or mist comprising the particles over the tacky film.

The control of the powder quality such as the particle size distribution, shape, and composition of the constituents has major influence on the development of the particle monolayer. Increasing the packing density in powders is usually accomplished by filling the interstices between large particles with smaller particle sizes. In order to increase the packing density of particles adhered to the tacky monolayer, the preferred particle distribution of the powder, measured by a coulter counter with a 50 micron aperture, is:

<u>Volume %</u>	<u>Size</u>
5	4,0 micron
25	8,3 micron
50	11,6 micron
75	14,8 micron
95	19,4 micron

FIG. 3 is a flow diagram showing the steps involved in an advantageous method of fabricating the white LEDs illumination devices. The first step, shown in Block A, is to provide a workpiece including one or more LEDs. A single LED is advantageously mounted in a cavity on a substrate and electrically connected as shown in Fig. 1. An array of LEDs is

advantageously mounted and connected in a cavity on a panel as shown in Fig. 2.

The next step, which is optional in some applications, is to mask the workpiece to cover areas of the workpiece which do not need to be coated with phosphor particles. The mask can be a reusable mechanical mask e.g. stainless, beryllium copper or a non-reusable mask such as plastic or paper. The mask will not be needed if the first optical material is selectively deposited such as by an automated dispensing machine using a syringe or pipette. The mask is also not needed if areas of the first transparent material are selectively made sticky, as, for example, by selectively exposing coated areas to a UV curing lamp.

The third step, shown in Block C, is to coat a transparent layer of tacky material over the LED(s). In order to create a monolayer of 5 to 25 microns in thickness, it is preferred to spin coat or spin remove the material using high rpm semiconductor spinning equipment. Panel wafers with mounted LEDs can be placed in the vertical position in order to maximize the removal of excess tacky material.

The next step (Block D) is coating the fluorescent phosphor particles on the tacky first transparent material. A monolayer can be deposited by spraying the particles at high velocity onto workpiece wafers. The surface of the tacky material will adhere only one to a few of the particles in depth, creating a monolayer which is not sticky. As a result, the particle coating is self-limiting. The particles will coat in all directions including the walls of the LED body as well as multiple contours.

The next step (Block E) is to cure the tacky material to cross-link the polymers. Curing can be done by heat curing, e.g. UV curing or microwave curing, or by other curing methods.

The 5th step (Block F), which is optional, is to deposit the second transparent layer of encapsulating material overlying the coated LEDs inside the cavity or cavities. The second encapsulating as noted above, forms a protective seal and optionally, forms a lens.

The next step shown in Block G, is to optionally dice the workpiece into a plurality of white LEDs or white LED arrays. A panel of coated and encapsulated LEDs can be diced

into individual pieces using a dicing saw or a water jet.

Fig. 4 schematically illustrates coating apparatus **600** to facilitate coating white LED workpieces **618** with phosphor particles **620**. In essence, the apparatus comprises an enclosed particle coating chamber **604** for receiving workpieces **618** to be coated. Chamber **604** is coupled to a reservoir **608** of particles to be coated, a source of pressurized gas **605** through a Venturi Nozzle **613** and a recycling chamber **611**. It includes enclosed openings for coated wafers **618** to exit and unused particles to pass to the recycling chamber **611**. Air flow **605** from an outside source, such as a blower or high pressure air compressor, is inserted into apparatus **600**. The air pressure can be approximately 100 PSI on an intake hose or tube. The air compresses into a nozzle **613** where the Venturi effect and the difference in pressures, forces the particles to the air stream from reservoir **608**. The force of the air flow is advantageously large enough to break any agglomerates in the phosphor powder, thus fluidizing the particles and dispersing them at high velocity. An air velocity of 10 to 15 feet per second is sufficient for this purpose. Mechanical dispersal of particles precludes the need for chemical dispersants for the phosphor particles. This is particularly advantageous since introduction of these additives can induce unwanted color nuances.

As the particles become fluidized, the coating process begins in the coating chamber **604** and deposits particles **620** randomly on top of the wafer **618**. The incoming panel feed transports wafers **617** into coating chamber **604**. Wafer **618** is shown in position to be coated. Excess particles **620**, not deposited into the wafer, move to the bottom of the chamber **619** and can be re-circulated by flow **604** into the system by back feed tube **607**. Back air pressure **609** can be created by vacuum source **601**. Flow **609**, created by suction caused by vacuum source **601**, passes through a powder filter **610**. Filter **610** can be paper or preferably sintered metal powder, which gets purged by a purging valve **602**, that is bridged from the incoming air stream **603**. The recycled particles can then drop by gravity into the bottom of the cyclone chamber **611** and into a screw feed **614**. Screw feed **614** can be controlled by stepping motor **612**. The screw feed can then move the phosphor particles back into the nozzle **613** by the Venturi effect and the cycle repeats again.

The present invention can now be better understood by the following non-limiting

examples of material combinations.

Example 1

Substrate Material: Copper Molybdenum Copper (Sumitomo Inc.)LED: UltraBrightTM InGaN LED (Cree Inc.)First Optical Material: NYOGEL OKT-0451 2 part silicone heat curable (NYE optical)Frequency Converting Material: YAG:Ce Phosphor (Phosphor Technologies UK)Second Optical Material: LED Encapsulant 9616 Dymax Corp

Example 2

Substrate Material: Copper Tungsten (Marketech Int. INC) LED: InGaN/GaN Blue LED's 3.3 (Epistar Corporation)First Optical Material: Sylguard - 2 part silicone heat curable (Dow Corning INC)Frequency Converting Material: YAG:Gd Phosphor (Phosphor Tech. USA)Second Optical Material: LS- 6257 Encapsulant (Light Span Corp)

The advantages of the inventive illumination devices and method are manyfold. An array of LEDs plus a mono-layer of fluorescent material can be used to create a light source having a uniform white light distribution, thus minimizing the "Halo Effect". Without wishing to be bound by theory, it is believed that the "Halo Effect" or bleed-through effect occurs because the light from the blue LED is directional while the yellow/amber from the phosphor radiates over 2π solid angle. Thus, an observer looking at a prior art LED from the side, can see a color that appears multi-color, not white. The single layer of fluorescent material as per the inventive technique, can coat multiple blue LEDs and create a uniform white light distribution in all directions.

Photonic emission recombination of wavelengths, usually from 360nm to 530nm, can be accomplished by an interaction between the host and the activator. The recombination can be attributed to the presence of an excited outer shell of the phosphor dopant ion. The emission band of the phosphor particles single crystal structure shifts of to a longer wavelength as the photon crosses the fluorescent material. The invention creates an efficient blue LED plus phosphor white light by minimizing the number of times that the photons have to pass through the wavelength converting material.

The blue LED approach is not limited to only one wavelength converting phosphor. It can be used with a two or three component phosphor system to generate high quality white. This option may use an ultra violet (“UV”) LED to excite several phosphors to simultaneously generate different colors. Multiple phosphors are preferred in order to increase the Color Rendering Index (“CRI”) of the light. Using such techniques, high color rendering indices similar to fluorescent lamps can be realized. The present invention can create a homogenous mix of the multiple phosphors by mechanically mixing phosphors at high speeds.

Scattering losses can be attributed to encounters with a particle or molecule as the electromagnetic wave propagates. The net effect is that the incident wave becomes partially re-radiated in different directions and hence loses intensity in its original direction of propagation. In order to minimize scattering loss, a single layer of fluorescent material in the form of a thin film layer of particles is preferred. Contrary to previous methods, the phosphor particles are not mixed in binders or epoxies. No matter how thin the layer is deposited, multiple particles in a binder will contribute to an increase in scattering losses. The applicant discloses a method in which a self limiting single layer of particles is attached to an optical dielectric film.

Optically matched dielectric material is critical for the reduction of total internal reflection (TIR). Snell’s Law relates the angles incidence and refraction angle θ to the refractive indices of the material (n), where the critical angle is given by $\sin \theta_c = n_2/n_1$, where n_1 is the index of refraction of the LED, and n_2 is the index of refraction of the coating. In order to minimize TIR, the preferred embodiment will coat the LED diode body with material having refractive indices that allow for maximum ray extraction from the semiconductor materials. At the same time the dielectric coating will allow particles of fluorescent material to attach to its surface creating a uniform conformal layer around its body.

In order to create the aforementioned coatings, a coating apparatus and manufacturing method had to be developed. The coating method includes a thin film layer of optically matched tacky material that is deposited prior to a uniform particles coating. The whole process occurs with the LED diodes already mounted and wirebonded to the thermal package

inside the cavity.

It is to be understood that the above-described embodiments are illustrative of only a few of the many possible specific embodiments which can represent applications of the principles of the invention. Numerous and varied other arrangements can be readily devised by those skilled in the art without departing from the spirit and scope of the invention.